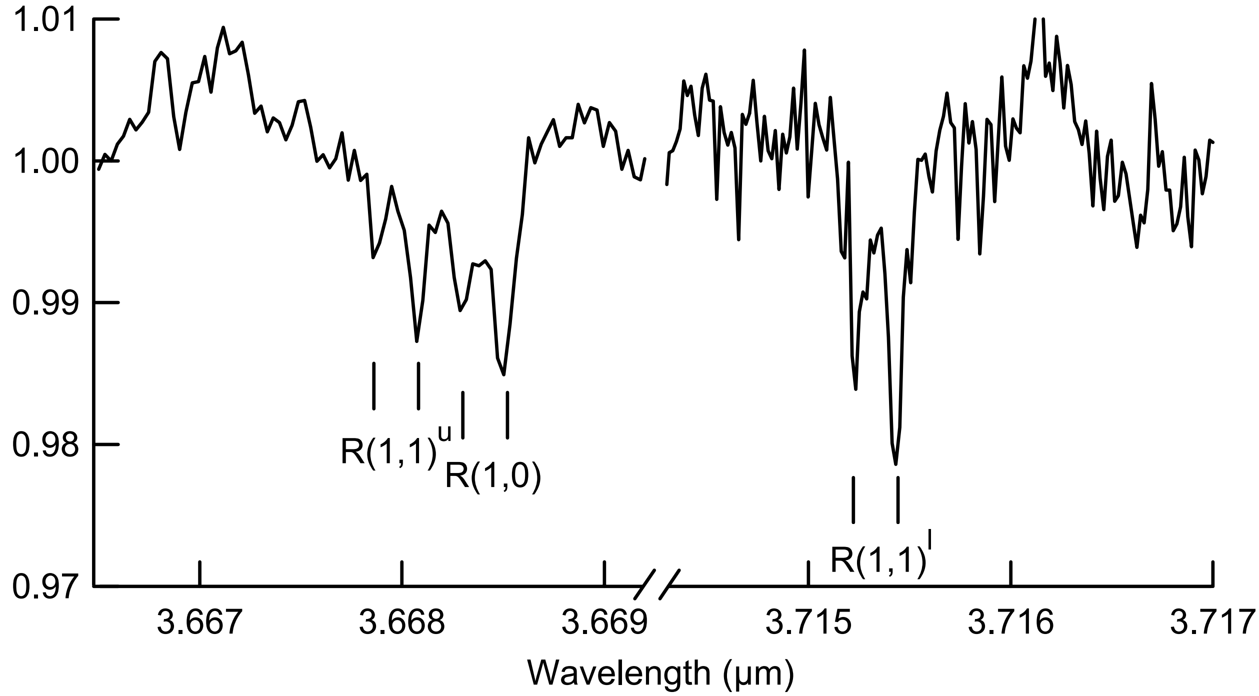
Observations of H_3^+ in the Diffuse Interstellar Medium



Ben McCall — University of California at Berkeley

Tom Geballe — Gemini Observatory

Ken Hinkle — National Optical Astronomy Observatory

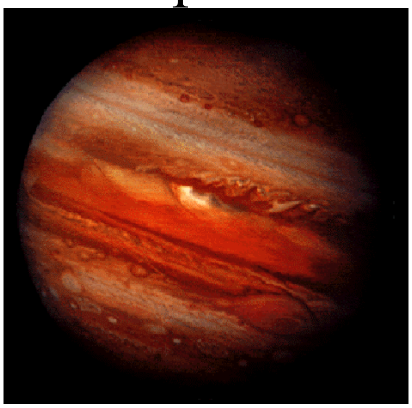
Miwa Goto
Naoto Kobayashi
Hiroshi Terada
Tomonori Usuda
— Subaru Telescope, National Astronomical Observatory of Japan

Takeshi Oka — University of Chicago

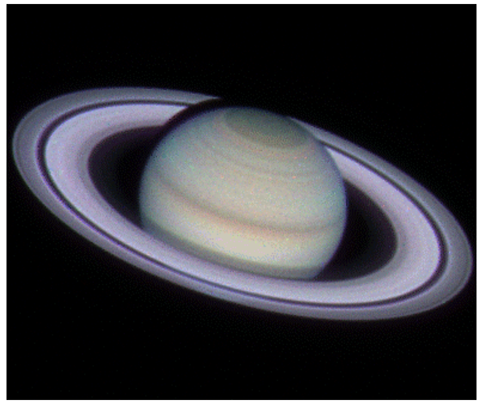
Ben McCall

Environments with H_3^+

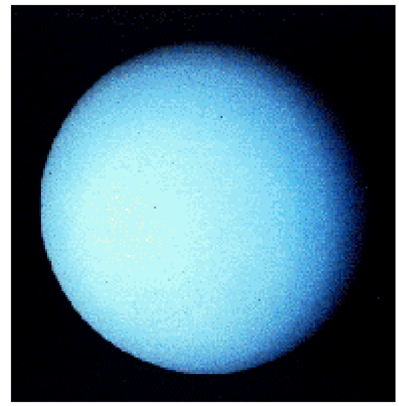
Jupiter



Saturn



Uranus



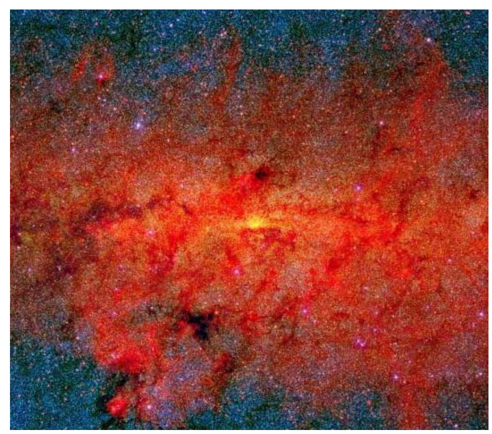
Dense Clouds

Barnard 68 (João Alves)

Diffuse Clouds

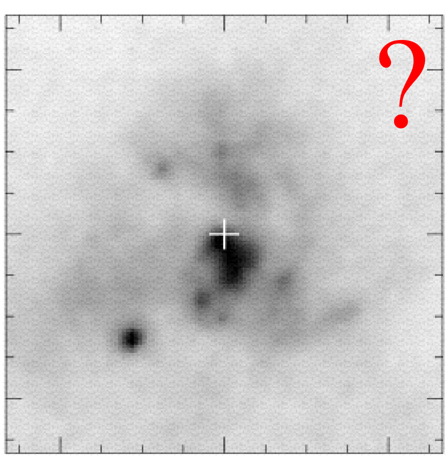
Cygnus OB2 (POSS)

Galactic Center



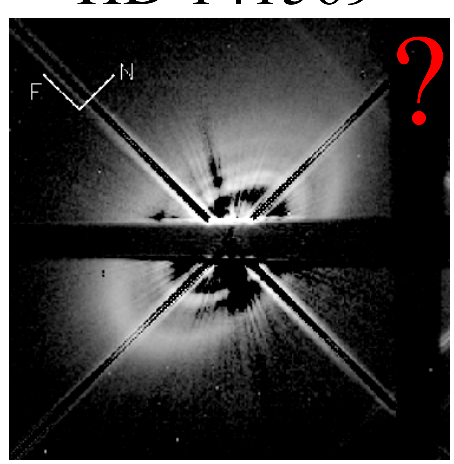
Galactic Center (2MASS/MSX)

IRAS 08572+3915



Goldader et al. ApJ 568, 651 (2002)

HD 141569



Mouillet et al. A&A 372, L61 (2001)

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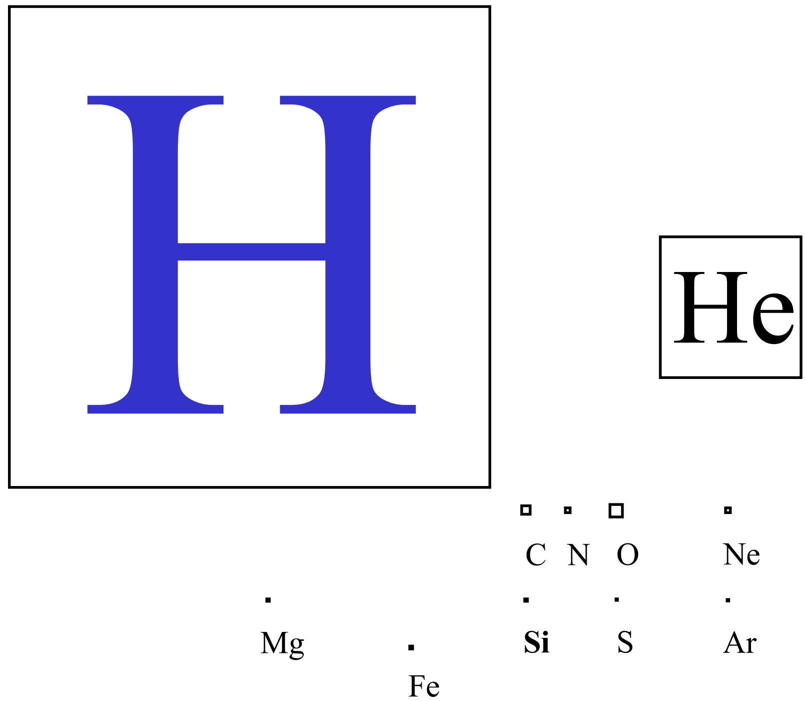
Importance of Interstellar H_3^+

Hydrogenic species of fundamental interest



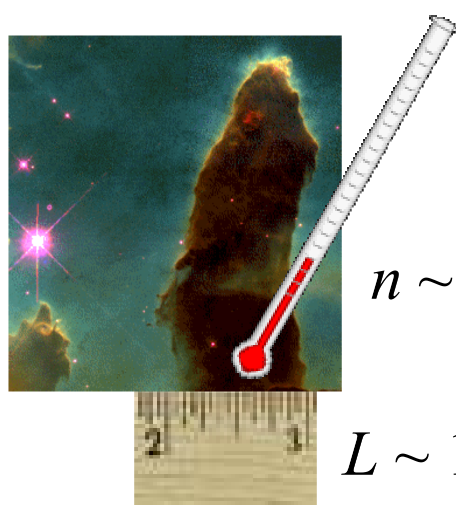
As "universal protonator," H_3^+ initiates ion-neutral reactions

$$H_3^+ + O \rightarrow H_2 + OH^+$$

$$OH^+ + H_2 \rightarrow H + H_2O^+$$

$$H_2O^+ + H_2 \rightarrow H + H_3O^+ \rightarrow H_2O$$

Simple chemistry → probe of cloud L, n, T



$T \sim 30$ K

$n \sim 10^5$ cm^{-3}

$L \sim 1$ pc

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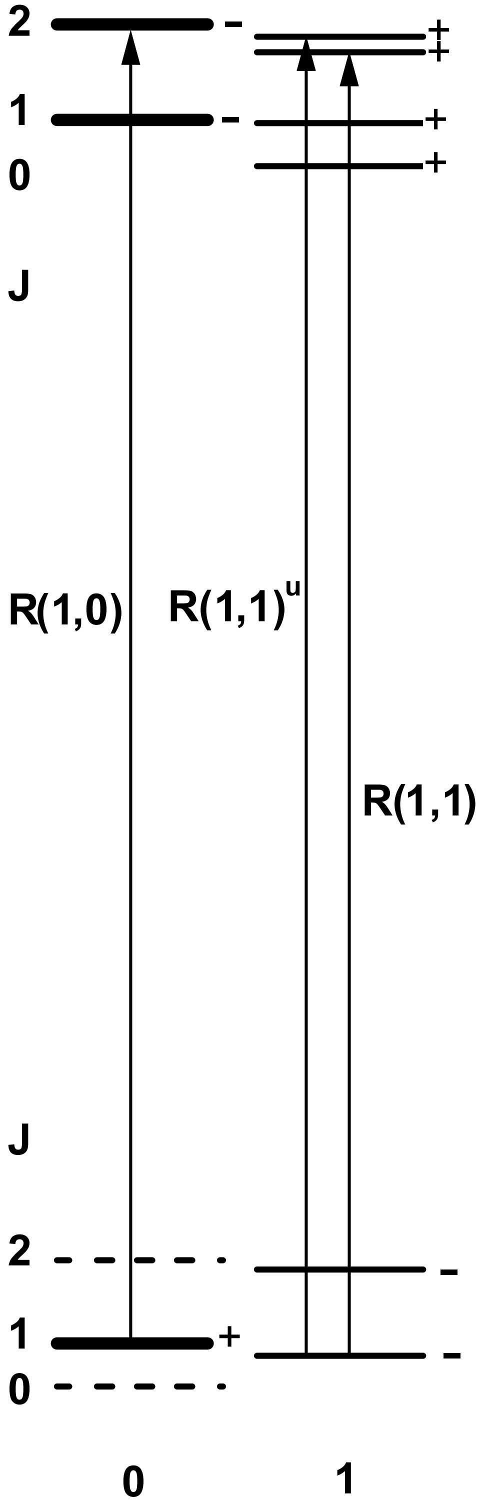
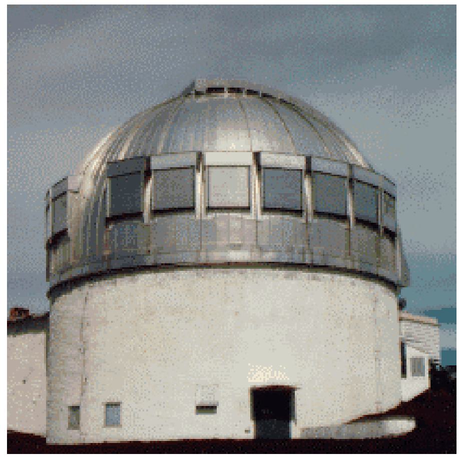
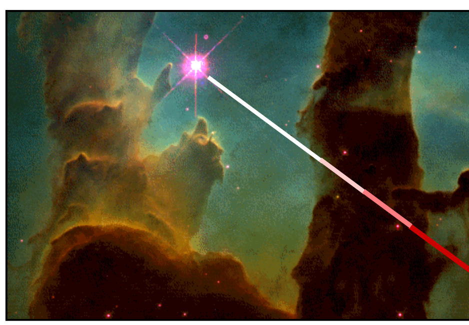
Spectroscopy of H_3^+



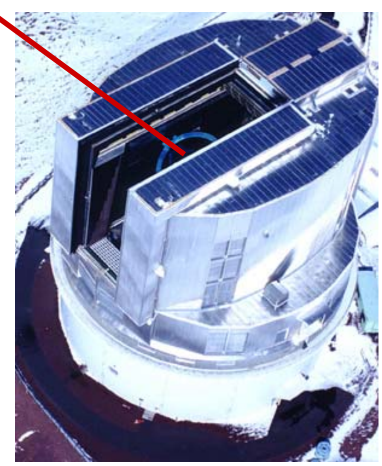


United Kingdom Infrared Telescope
Mauna Kea, Hawaii

Nicholas U. Mayall Telescope
Kitt Peak, AZ



Subaru Telescope
Mauna Kea, Hawaii



Integrated area of absorption lines

↓

H_3^+ column density $N = [H_3^+] \times L$

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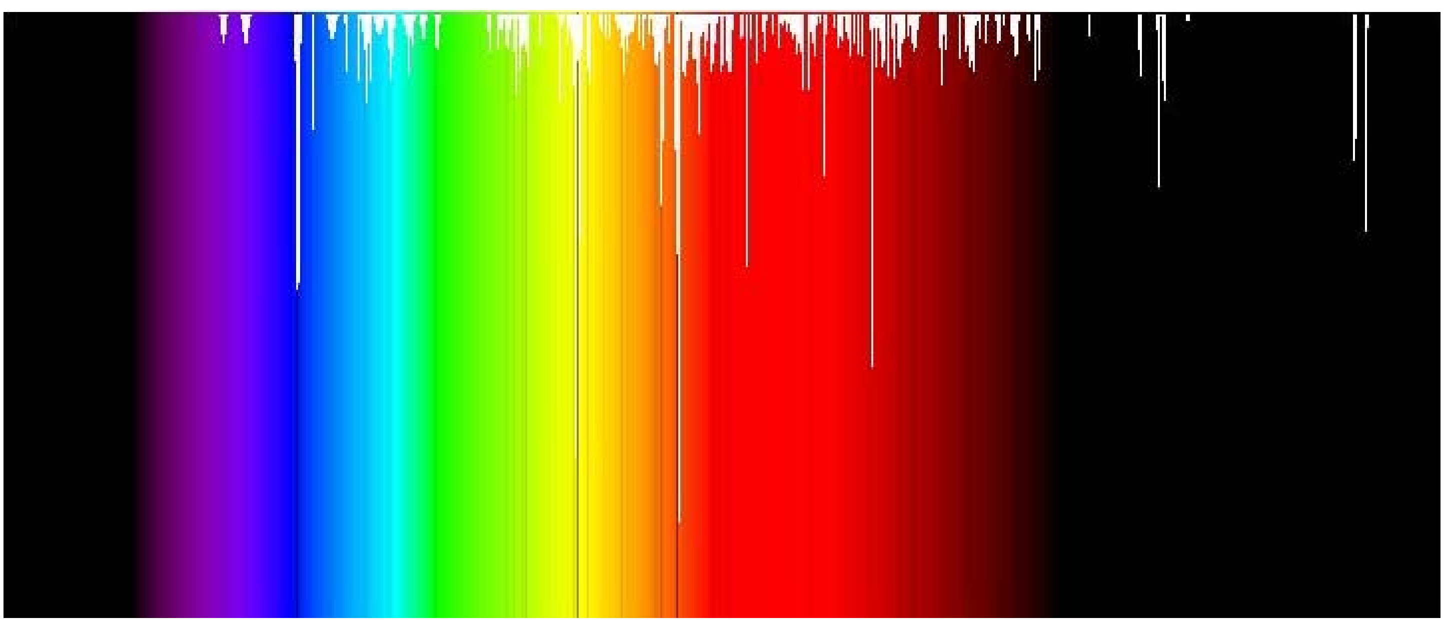
Diffuse Cloud Environment

- Little dust → reasonable visible/UV flux
- $[H] \sim [H_2] \sim 100\ cm^{-3}$ [low density]
- $C + h\nu \rightarrow C^+ + e^-$ [high electron fraction]
- $L \sim 10$ pc
- $T \sim 30$ K
- Diatomics observed (CH, CH^+, CN, C_2, CO, OH...)
    - CH^+ (over)abundance a mystery
- Until recently, no polyatomics (now H_3^+, C_3)
- Diffuse Interstellar Bands:



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H_3^+ Chemistry

Formation:

$$H_2 \xrightarrow{\text{cosmic ray}} H_2^+ + e^-$$

$$H_2 + H_2^+ \rightarrow H_3^+ + H$$

Rate = $\zeta\, [H_2]$

Destruction:

$$H_3^+ + e^- \rightarrow H + H + H$$

$$\rightarrow H + H_2$$

Rate = $k_e\, [H_3^+]\, [e^-]$

Steady State:

$$[H_3^+] = \frac{\zeta}{k_e} \cdot \frac{[H_2]}{[e^-]} \sim 10^{-7}\,\text{cm}^{-3}$$

(very low due to efficiency of electron recombination)

Over a typical diffuse cloud pathlength of 10 pc,

$$N(H_3^+) = [H_3^+] \times L$$

$$= (10^{-7}\,\text{cm}^{-3}) \times (3 \times 10^{19}\,\text{cm})$$

$$\sim 3 \times 10^{12}\,\text{cm}^{-2}$$

NOT DETECTABLE!

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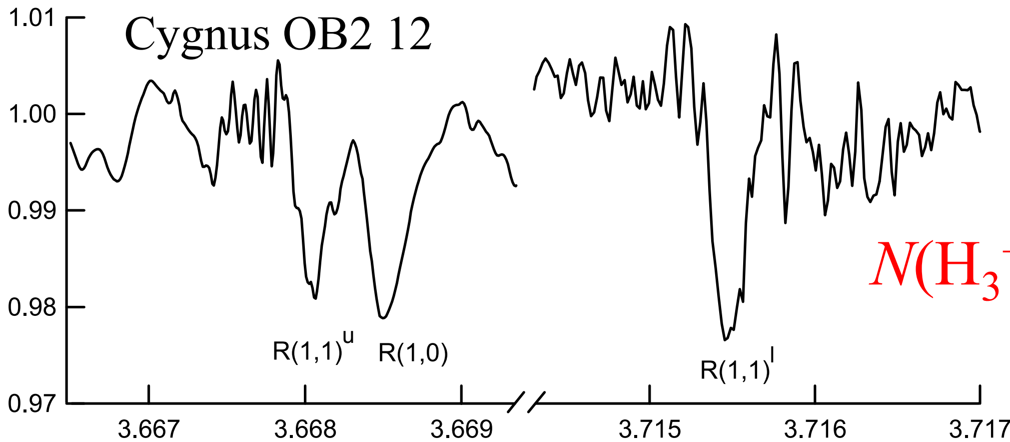
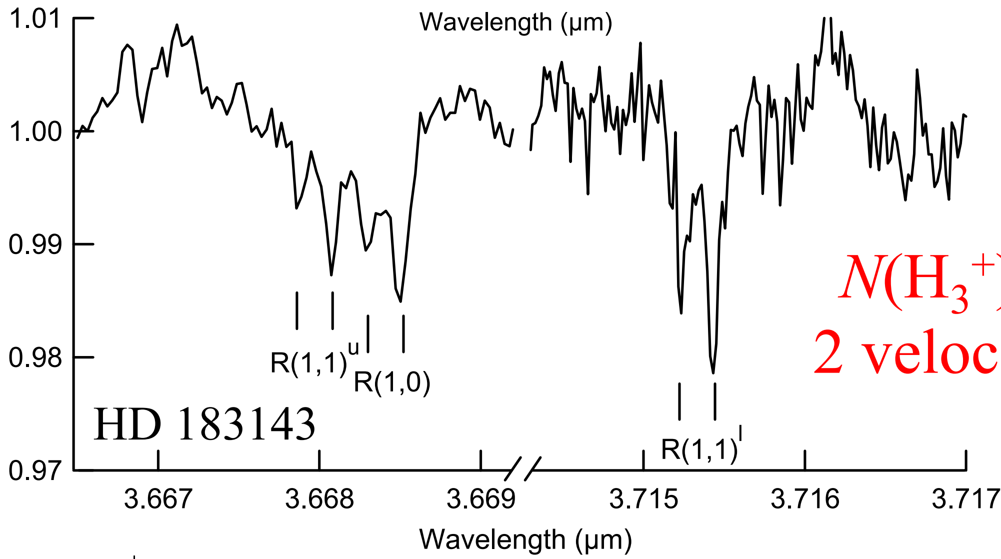
H_3^+ in Diffuse Clouds!

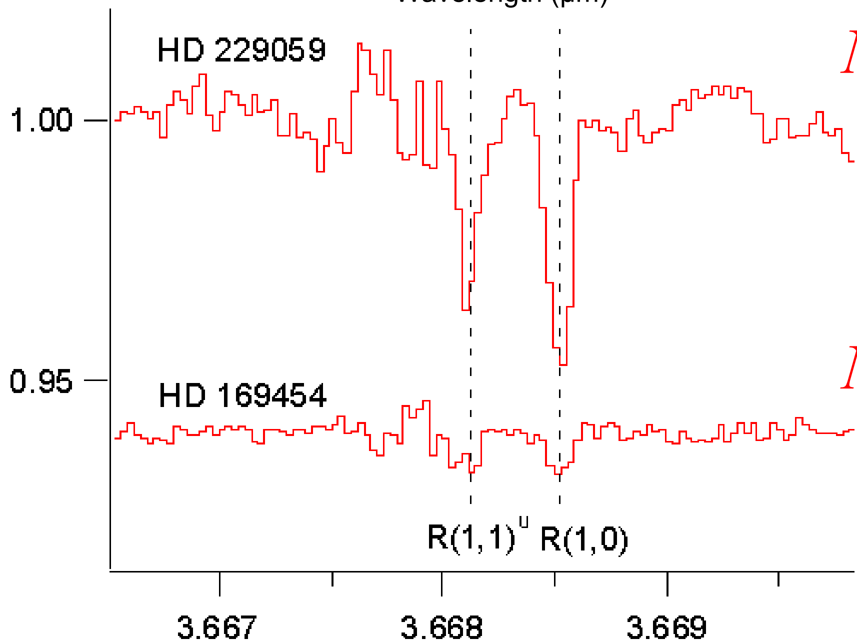


$N(H_3^+) \sim 3\times10^{14}$ cm^{-2}



$N(H_3^+) \sim 3\times10^{14}$ cm^{-2}

2 velocity components!



$N(H_3^+) \sim 3\times10^{14}$ cm^{-2}

$N(H_3^+) \sim 7\times10^{13}$ cm^{-2}

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Inferred Cloud Parameters

Object	E_{B-V}	d(pc)	L(pc)	<[H]>
Cyg OB2 12	3.35	1700	905	4.8
Cyg OB2 5	1.99	1700	629	4.1
HD 183143	1.28	1000	552	3.0
HD 20041	0.70	1400	833	1.1
WR 121	1.68	1690	524	4.1
WR 104	2.10	1300	595	4.5
WR 118	4.13	6300	1310	4.1
HD 229059	1.71	1000	725	3.0
HD 169454	1.12	930	169	8.5

- Path lengths too long (most of way to stars!)
- Number densities too low ($H_2 \rightarrow H$!)
- Conflict with other measurements (e.g. C_2)

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Chemical Model

$$[H_3^+] = \frac{\zeta}{k_e} \cdot \left(\frac{[e^-]}{[H_2]} \right)^{-1}$$

- Uncertain parameters:
  - $[e^-]/[H_2]$ — electron fraction
    - we assume $C + h\nu \rightarrow C^+ + e^-$
    - ionization incomplete in “translucent” clouds?
  - k_e — electron recombination rate
    - could be lower than experiments indicate?
    - controversial field — recent results
  - ζ — cosmic ray ionization rate
    - can’t measure from satellites
    - “measured” in dense clouds
    - could be higher in diffuse clouds?

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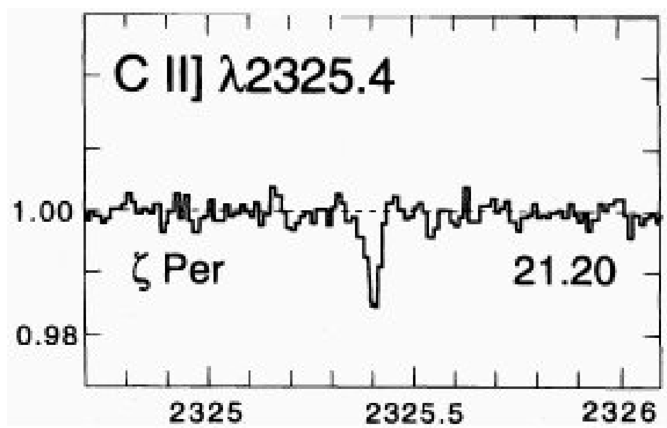
Electron Fraction $[e^-]/[H_2]$

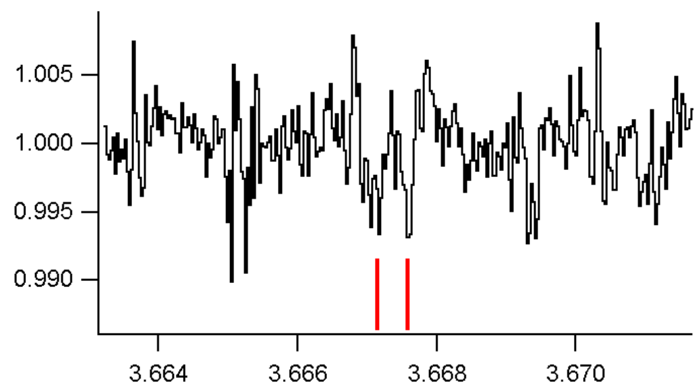
$$[H_3^+] = \frac{\zeta}{k_e} \cdot \left(\frac{[e^-]}{[H_2]} \right)^{-1}$$

- $N(e^-) = N(C^+)$ — HST (UV bright)
- $N(H_2)$ — Copernicus, FUSE (UV bright)
- $[e^-]/[H_2] \sim N(C^+)/N(H_2)$
  - few stars with both
  - ζ Per: 4×10^{-4}
  - assumed value okay

Cardelli et al. ApJ 467, 334 (1996)



- H_3^+ toward ζ Per?
  - tentative detection
  - UKIRT, Sep '01
  - rules out $[e^-]/[H_2]$ as culprit (?)



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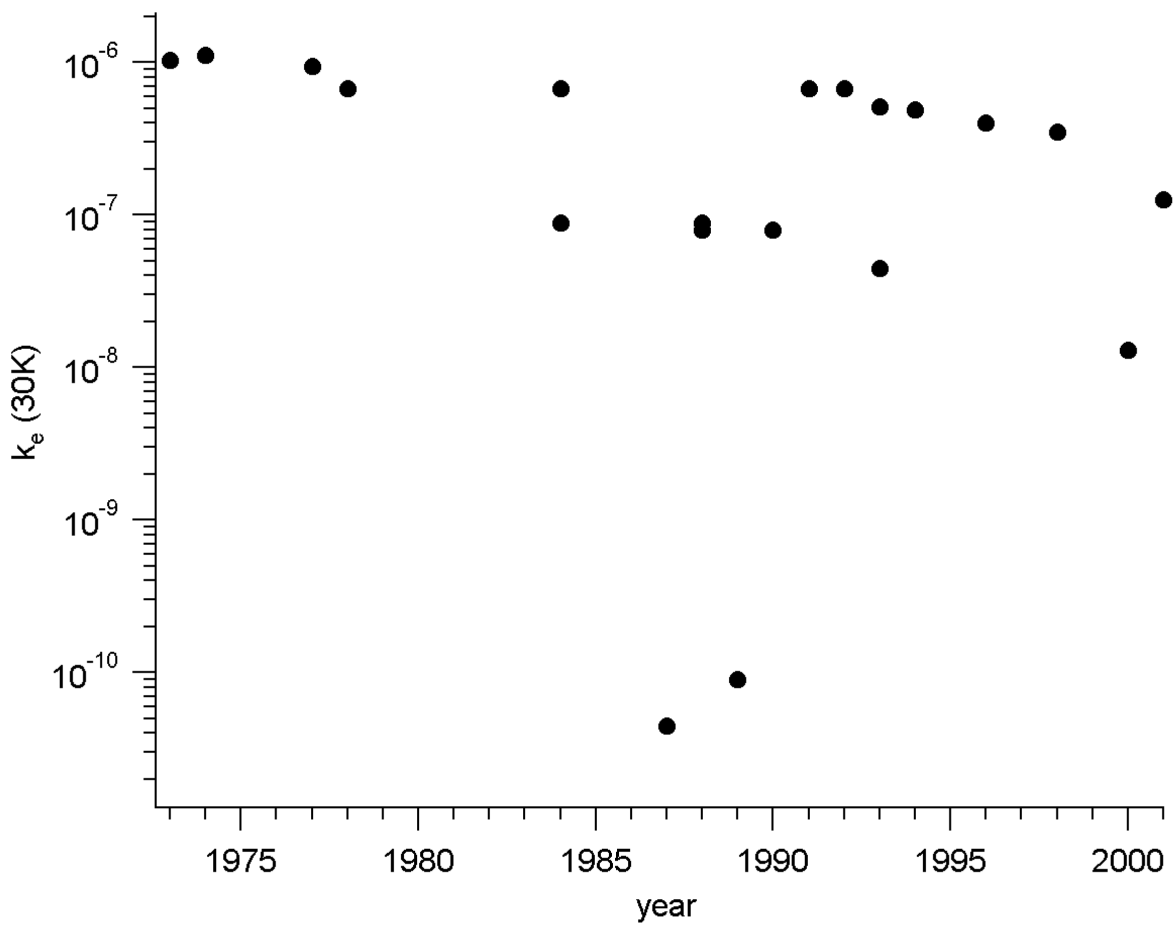
Recombination Rate k_e

$$[H_3^+] = \frac{\zeta}{k_e} \cdot \left(\frac{[e^-]}{[H_2]} \right)^{-1}$$

- Discrepancies among measurements
- Discrepancy between theory & experiment
- Really need to measure k_e for J=1 H_3^+



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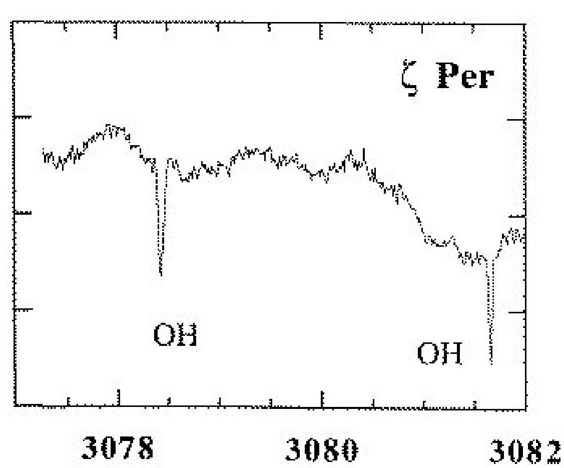
Cosmic Ray Ionization ζ

$$[H_3^+] = \frac{\zeta}{k_e} \cdot \left(\frac{[e^-]}{[H_2]} \right)^{-1}$$

- Unconstrained by "local" measurements
- Well constrained in dense clouds
  - chemical models ($[DCO^+]/[HCO^+]$, etc.)
  - H_3^+ observations give reasonable lengths
- Poorly constrained in diffuse clouds
  - population of low-energy cosmic rays?
  - only handle is OH chemistry
  - for ζ Per, 2.2×10^{-17} s^{-1}
  - for o Per, 2.5×10^{-16} s^{-1}
  - OH chemistry uncertain?

Felenbok & Roueff, ApJ 465, L57 (1996)



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Conclusions

- H_3^+ observed in 13 diffuse cloud sources
- Upper limits in several others

- H_3^+ consistently overabundant
- Derived path lengths way too long!

- Two order of magnitude problem:
  - either $[e^-]/[H_2]$ lower than we think
  - or k_e is smaller than we think
  - or ζ is larger than we think

- Third enigma of diffuse cloud chemistry (along with CH^+ and DIBs)

For more information, visit http://dib.berkeley.edu